Embedded Control System for Stimulation-Driven Exoskeleton*

Lu Li, John R. Schnellenberger, Mark J. Nandor, Sarah R. Chang, Kevin M. Foglyano, Ryan-David Reyes, Rudi Kobetic, Musa Audu, Ronald J. Triolo, and Roger D. Quinn

Abstract—**This paper presents the design and deployment of a modular, portable and inexpensive embedded control system architecture for the hybrid neuroprosthesis (HNP). It consist of a suite of custom designed electronic hardware and firmware to provide wireless connectivity for close-loop control with mechanical exoskeletal constraints and neural stimulation with provisions for power assist to restore locomotion functions for individuals with spinal cord injury (SCI). The design philosophy, methodology, and implementation are described and discussed in details. Bench testing and subject experimentation have been conducted to evaluate the performance of the HNP system. We conclude that the embedded control system meets the technical requirements and design criteria, and can thus be considered as a potential reference design for generic biomedical research and clinical deployment in the neuroprosthetic and exoskeleton fields.**

I. INTRODUCTION

Exoskeleton and Functional Neuromuscular Stimulation (FNS) can both restore locomotion and mobility for individuals with spinal cord injury (SCI) [1], [2], [3]. Exoskeletons powered by hydraulics or electric motors [4], [5], [6], can produce significant amounts of torque output, but suffer from bulkiness, higher cost, and limited run-time. Other approaches, especially a hybrid method of combining muscular stimulation with other light weight actuators or passive mechanisms, enable an increase in power efficiency, reduced weight, and most importantly allow the paralyzed muscles to be exercised during assisted walking [7], [8], [9].

A hybrid method combining FNS with passive mechanisms can increase power efficiency and reduce weight.The muscles produce the joint torque required for locomotion and passive bracing mechanisms support load and allow the individual to rest with no energy expense. Furthermore, the paralyzed muscles are exercised during walking, which provides many health benefits [1].

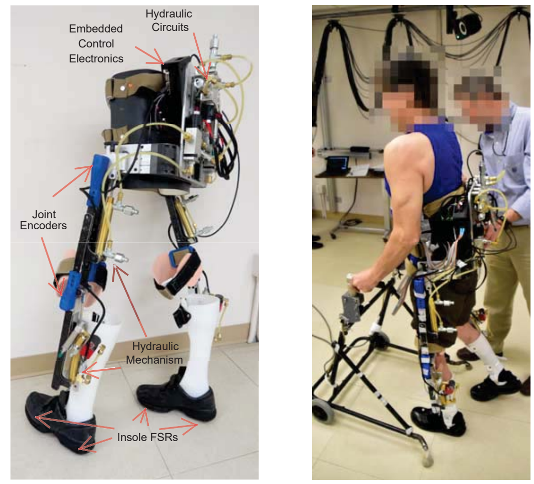
The second generation Hybrid Neuroprosthesis (HNP) [10] combines FNS, for powering the joints, and a passive hydraulic exoskeleton that locks, unlocks or couples joints appropriately during the gait cycle or when standing. It was equipped with various proprioceptive sensors and hydraulic valves and cylinders. It is suitable for individuals with an implanted FNS system [11].

*This work was supported by Departments of Veterans Affairs, Defense Grants and Case Western Reserve University (CWRU).

L. Li, M.J. Nandor, and R.D. Quinn are with the Department of Mechanical Engineering, CWRU and the APTC, Cleveland, OH, 44120 (email: lxl361@case.edu; mjn18@case.edu; rdq@case.edu).

S.R. Chang, R.D. Reyes, and R.J. Triolo is with the Biomedical Engineering, CWRU and the APTC, Cleveland, OH, 44120 (e-mail: sarah.r.chang@case.edu, rxr410@case.edu, ronald.triolo@case.edu).

J.R. Schnellenberger, K.M. Foglyano, M.Audu, and R. Kobetic are with the APTC, Cleveland, OH, 44120 (e-mail: jschnel@aptcenter.org; kfoglyano@fescenter.org; rkobetic@fescenter.org).



a). b).

Fig. 1. a). HNP Exoskeleton hardware and b). individual with SCI walking with HNP.

TABLE I
TECHNICAL SPECIFICATIONS OF THE HNP ELECTRONICS

Main Processor	Ateml ATmega2560
Max. Operating Freq.	16Mhz
On-chip memory (Bytes)	256k Flash, 8k SRAM, 4096 EEPROM
Digital IOs	32 max (16 if use analog IOs)
Analog IOs	16 channels (10-Bit@15ksps ADC)
PWM Channels	15 channels
UART	4 Channels (Full Duplex)
SPI	1 Channel
I2C	1 Channel
USB	CP2012 USB-UART Bridge
Wireless Subsystem	Bluetooth 2.0 EDR
IMU Subsystem	9-axis w/ fusion (Atmega328+MPU9150)
Max Power consumption	5VDC@100mA
ECB Dimensions	30mm (W) x 60mm (L) x 5 mm (H)

To control this complex cyber-physical system, we have designed an embedded hardware system and developed the control firmware/software to achieve untethered gait restoration for people with SCI wearing the HNP. Open-source microprocessor electronics [12], wireless communication [13], [14] and sensor fusion technologies [15], [16] are incorporated. We designed it with a goal of it being a generic embedded system architecture, which would be a reference design for biomedical research and clinical deployment. Table I shows the technical specification of the embedded control system.

II. Design Methods

A. System Level Analysis and Modeling

During the initial phase of the design process, system level analysis and modeling were carried out to understand the technical requirements and design criteria. The HNP design is composed of three functional layers of cyber-physical and mechatronics building blocks, as shown in Fig. 2.

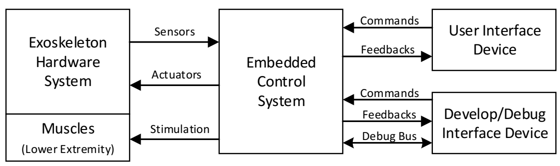


Fig. 2. High-level System overview of the functional layers.

The physical layer includes the exoskeleton hardware and the lower extremity muscle groups, which interacts with the physical world by hydraulic and muscular actuators, while obtaining feedbacks using sensors. The onboard processing layer provides necessary synthesis and coordination of inputs, controls, outputs, and interfaces. One of the main components in this layer is the embedded control system, which acts as the ”artificial cerebellum and spinal cord” of the HNP users. On the right side of Fig. 2 the user interface layer, which enables the user to send commands and receive system status information via mechanical switches and graphical interface, and also allows researchers to program and monitor the system by developing/debugging interfaces between the HNP and external computers.

Advancements on our previous HNP system introduced several new elements to provide sensory feedback, close-loop control, FNS-stimulation, and wireless connectivity, to improve the restoration of locomotion functions for individuals with SCI. For example, we added an inertial measurement unit (IMU) to determine posture and body orientation, an onboard processor replaced the stationary and bulky external control software xPC target machine [17], and wireless connectivity for smartphone-based Graphical User Interface (GUI) was introduced to improve user experience. The tree diagram shown in Fig. 3 lists the dependent hardware components in the HNP system, including sensors, actuators, processing, and develop/debug groups.

The electrical system architecture (shown in Fig. 4) for the HNP system is partitioned into five core hardware systems, the hybrid orthosis system, the signal conditioning board (SCB), the embedded controller board (ECB) stacks (contains the IMU subsystem and Bluetooth wireless subsystem), the FNS boards, and the battery power supply. These architecture diagram describes the interconnection and hierarchy of the hardware devices, and the implementation details will be discussed in section II and III of the paper.

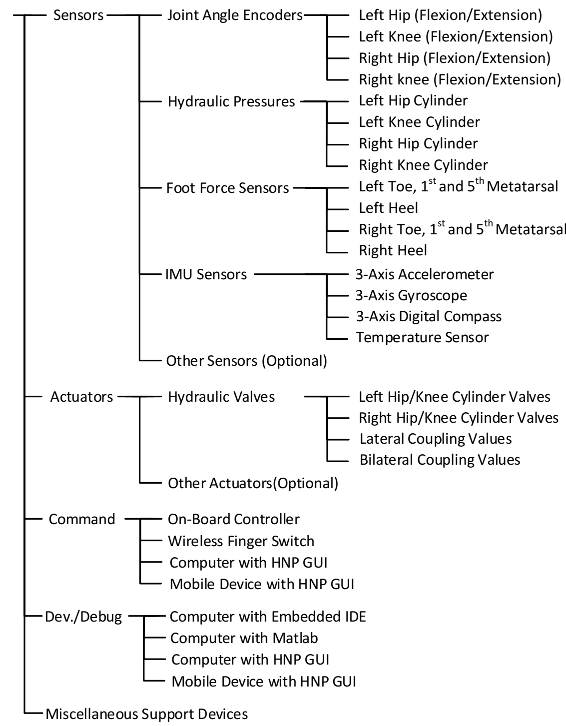


Fig. 3. Tree diagram of the core hardware devices.

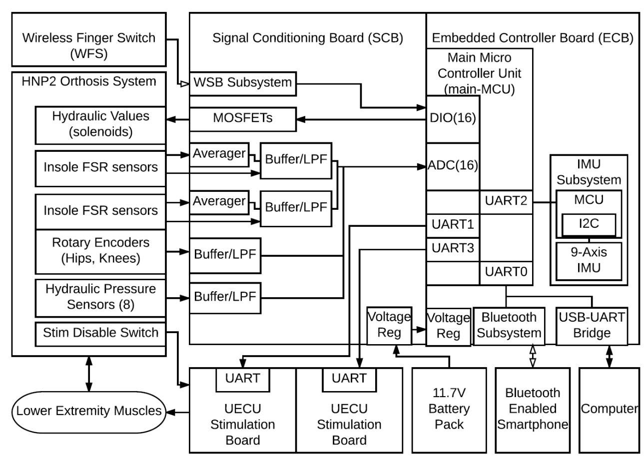


Fig. 4. HNP ECB electrical system architecture overview.

B. The Hybrid Orthosis System

The exoskeleton portion of the HNP system consists of a mechanical frame and hydraulically locked and unlocked joints. While the joints are passive and do not actively contribute any energy to the system, the brace and the hydraulics act to constrain the kinematics of the motion to the sagittal plane and to provide stability while stimulation provides power for movement. Additionally, stimulation-only-gait is typically run in an open loop pattern; the addition of sensors to the exoskeleton frame enable the system to detect different phases of gait and apply stimulation or power assist and joint constraints accordingly to maintain walking.

A summary of the exoskeleton's mechanical and hydraulic subsystems can be found in [11], [10]. Briefly, the exoskeleton consists of two hydraulic systems a knee joint system that can lock and unlock via a solenoid-actuated hydraulic valve, and a hip joint system able to lock, unlock, and reciprocally couple the hip joints (left hip flexion causes right hip extension, and vice-versa). Hydraulic cylinders are connected to the exoskeletal frame via three bar transmissions that translate the linear motion of the cylinders to rotary motion of the joint.

C. Embedded Controller Board (ECB) System

The Embedded Controller Board (ECB) hardware was designed, manufactured, and tested for the HNP. The ECB design follows a modular approach in both external integration and internal integration aspects. The external integration modularity has standardized physical dimensions and electrical connectors (SCB-ECB board-to-board interface), which allows the ECB to act as a standalone module and can be swapped or replaced from the SCB or other motherboards. Internal integration modularity defined the subsystems such as the IMU and wireless modules which are hardware independent and interchangeable daughterboards through three castellated PCB mounting interfaces at the bottom of the ECB. External and internal modular designs enable any individual board level hardware revision without changing host and dependence hardware, thus reducing development risks and improving upgradability. The functional block diagram and modular architecture of the ECB system is presented in Fig. 5.

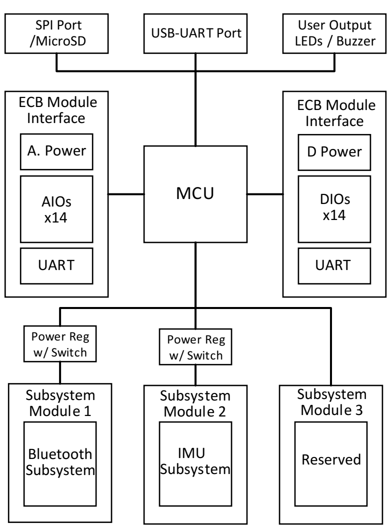


Fig. 5. The ECB modular design functional block diagrams.

The ECB is a custom designed PCB assembly containing eight core components (see Fig. 6). The main processor of the ECB is an ATmega2560 8-bit AVR microcontroller (Atmel Co., San Jose, CA, USA), which samples the orthosis analog sensor signals via the SCB-ECB analog bank connector and generates the hydraulic valve and stimulation control signals via the SCB-ECB digital bank connectors. A Universal Asynchronous Receiver/Transmitter to Universal Serial Bus (UART-USB) bridge IC (Silicon Labs CP2102) and connector (MicroUSB) enables programming a debugging interface between ECB and a computer. Furthermore, the ECB also containes the Inertial Measurement Unit (IMU) subsystem module for step initiation or balance control, and the Bluetooth wireless subsystem module for interfacing with another Bluetooth enabled mobile device or computer to receive command and monitor system data. In addition, an optional MicroSD card slot provides up to 4GB storage capability for large size data recording without filling up the limited microcontroller memory size. Lastly, an onboard 5V to 3.3V power regulation circuit can be used to selectively power up the subsystems, provide a controllable power-up sequence between the main microcontroller and two subsystems.

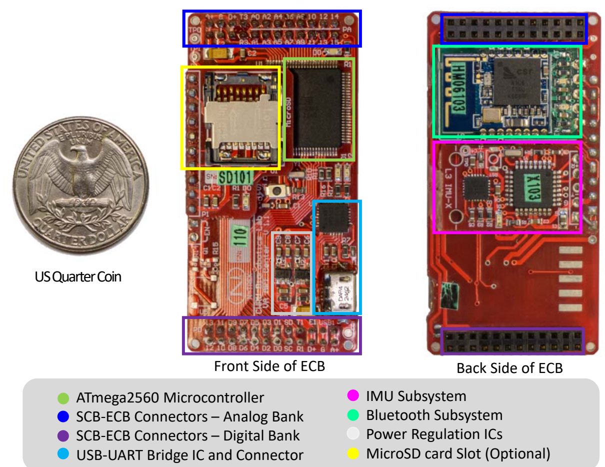


Fig. 6. The HNP ECB assembly with components map.

To make the control electronics for the HNP exoskeleton, affordable and accessible for more individuals with SCI, the ECB is designed for low-cost and mass-production. A panelized two-layer PCB plan was created, which places all system required subsystem modules together with the ECB main board on one board panel, and all surface mount components on the topside for straightforward automatic pick-and-place assembly and reflow soldering manufacturing. The PCB panel of the ECB before final assembly is shown in Fig. 7.

D. Bluetooth Wireless Subsystem

The wireless subsystem is the digital communication bridge between the HNP hardware and an external device, such as a handheld mobile device or a personal computer [18]. In this design, the Bluetooth 2.0 protocol was the selected wireless solution.

The HM-06 Bluetooth 2.1 Enhanced Data Rate (EDR) to UART converter module (Huamao Technology Co,. Ltd.) is selected for the Bluetooth wireless subsystem due to its minimal integration for both hardware and firmware development

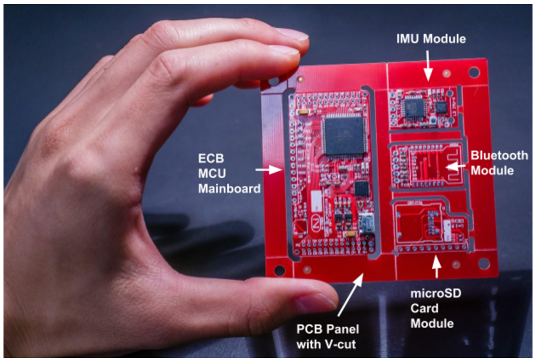


Fig. 7. NHP2 ECB and subsystem boards assembly.

on any UART-enabled microcontroller system. The Bluetooth connection to the ECB map to UART channel 0 at a baud rate of 115200 bps, which was also shared between the UART-USB bridge to reduce the pin count.

E. Inertia Measurement Unit Subsystem

The IMU Subsystem is a miniature PCB that contains motion measurement and a dedicated co-processor for onboard sensor fusion and filtering computation. The main sensor is a 9-axis MEMS-based IMU MPU-9150 (InvenSense, Inc. San Jose, CA) capable of sensing ± 16 channels of acceleration signal, $\pm 2000°$/sec angular rate, and $\pm 1200\mu$T digital compass. The main function of the co-processor is to record body trunk acceleration and orientation to detect fall, establish a stable posture and initiate locomotion. With the help of open-source software libraries, we implemented the raw 9-axis data output, complimentary filter, Kalman filter, and AHRS fusion on the IMU subsystem. Varied type of data output format, such as unscaled data, regular angle, and quaternions, can be selected using the UART communication protocols for research and experimental purposes. More importantly, these computationally expensive algorithms are run on the co-processors to improve overall system efficiency by offloading the central processor, while only transmitting time-stamped sensory data between ECB and IMU subsystem.

F. Muscular Stimulation Board System

The HNP supports four types of FNS board hardware, and enables up to two board configurations with arbitrary types of stimulation methods. Two UART data channels with ECB are established when connecting the stimulation boards to the SCB, enabling command and error handling protocol transmission between the two systems. The stimulation boards were developed by Cleveland FES Center [19], and the board types supported are described below.

- Surface Stimulation Board, provides up to 4 channels of bipolar, constant-current, biphasic stimulation with a stimulation amplitude range of 0 to 100mA, a pulse width range of 0 to 255μs, and a compliance voltage of 150V.
- Percutaneous Stimulation Board, provides up to 12 channels of constant-current, biphasic stimulation with a stimulation amplitude range of 0 to 20mA, a pulse width range of 0 to 255μs, and a compliance voltage of 50V.
- Implant Control Board, Controls/interfaces with implantable stimulators via an external coil. It powers the implant and sends commands to it via RF modulation (on-off keying). The 8-channels implant and 16-channels implant are described below.
  - Implanted Receiver-Stimulator (IRS-8), provides up to 8 channels of constant-current, biphasic stimulation with amplitudes of 0, 2mA, 8mA, 14mA, or 20mA, a pulse width range of 0 to 255us, and a compliance voltage of 30V.
  - Implanted Stimulator-Telemeter (IST-16), Provides up to 16 channels of constant-current, biphasic stimulation with amplitudes of 0, 0.1mA, 0.8mA, 1.4mA, 2.1mA, 18mA, 18.7mA, 19.3mA, or 20mA, a pulse width range of 0 to 255μs, and a compliance voltage of 30V.

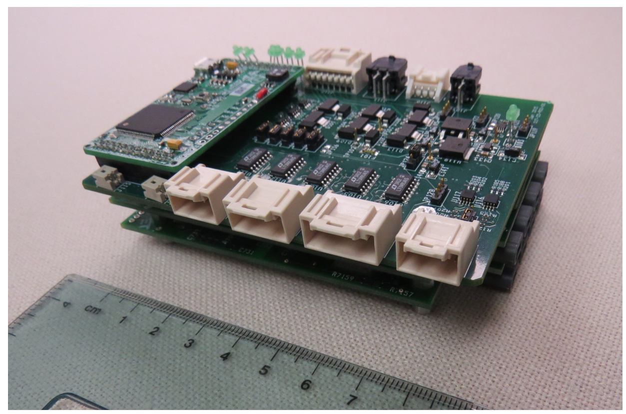


Fig. 8. ECB and SCB assembly as the HNP controller unit.

G. Signal Conditioning Board (SCB) System

The SCB is a single (6 layer) PCB acting as the central hub of the HNP system, which provides signal conditioning, power supply, and connector interface between HNP exoskeleton hardware/sensors, ECB, and Universal External Control Unit (UECU) stimulation boards. The analog circuitry receives and conditions sensor signals from left and right foot sensing resistors (FSRs) placed between the Ankle-Foot Orthoses (AFOs) and shoes, signals from encoders at hips and knees, and signals from hydraulic pressure sensors. The SCB also provides control/drive signals for six 12V, 1.4A hydraulic valves by using Fairchild FDT86113LZ MOSFETs (100V, 3.3A). The SCB also passes control signals from the ECB to the stimulation boards. The SCB contains board-to-board connector interfaces for the ECB, up to two stimulation boards, and board-to-cable connectors for sensors and actuators on the exoskeleton hardware. Finally, the SCB generates the necessary voltages (power supplies) for circuitry, sensors, , and other system boards such as ECB and stimulation boards. This includes 11.5V, 5V, and 3.3V.

The assembled electrical and control hardware system forms a compact board sandwich assembly, which consists of an ECB, an SCB, and two stimulation boards from top to bottom, as shown in Fig. 8.

III. Embedded Firmware Design

A. Main Control Firmware

Sensors enable the embedded electronics to detect the user's phase of gait and apply the correct joint locking/coupling constraints and stimulation parameters. Absolute magnetic encoders (U.S. Digital) measure each hip and knee joint angles, which send analog voltages as output to be read by the system controller. Heel strike and toe-off events are detected by force sensitive resistors (FSRs) (BL Engineering) at the heel and forefoot. The FSRs are integrated into the shoe sole, with three sensors placed in the forefoot, and one in the heel.

The sensor data are acquired at 50 Hz by the onboard microcontroller, and the onboard Gait Event Detector (GED) within the Finite State Machine (FSM) determines the current phase of gait. As certain thresholds are detected by the GED, the FSM moves progressively through the stance and swing phases of the programmed gait [11]. Intent and broad level control are input to the system by a wireless finger switch held in the users hand. While the FSM is operated independently on the embedded electronics onboard, a Bluetooth link to a laptop records data for postprocessing and analysis, and allows clinicians to adjust stimulation parameters and GED threshold settings. For a complete explanation, see [11], [10].

B. FNS Control Firmware

The stimulation control system requires the capability of controlling multiple stimulation system types on a single embedded system. There are two major challenges of the design: software modularity and computational efficiency.

First, due to the fact that the FNS system development is parallel to the main controller research, we designed the FNS stimulation firmware as a modular software library. Thus, its firmware can be added, modified or removed without affecting the other code bases in the same controller firmware, while also easily interfacing with other programs. We developed two version of the FNS control software library both in C and C++ language, to guarantee portability of the code and enable software modularity and support cross platform compiling capability on both embedded and regular computer system.

Second, the firmware needs to be computationally efficient when calculating stimulation patterns and coordinating with rapidly changing signals. To achieve this goal, we designed a smart stimulation pattern scheduler software, which controls up to 16 channels of FNS signals independently per stimulation board, with real-time pulse width ramping generation for smooth muscle output and reduced fatigue. The scheduler automatically computes a 10,000 sample point per channel per gait cycle stimulation pattern from a pre-scripted gait parameter file, while able to dynamically perform the stimulation pulse width modulation and amplitude modulation at a programmable interval.

IV. Experiments

A. Able Body Walking

Able-bodied testing was performed to demonstrate overall system safety, functionality, wireless data collection, and data processing. Two able-bodied volunteers from this research team signed the local IRB-approved consent forms to evaluate the HNP system during walking. Subjects were able to walk in the exoskeletal system safely (Fig. 9). The exoskeletal joint constraints locked and unlocked appropriately according to the finite state machine programmed on the embedded controller. Inertial measurement unit (IMU) data, joint angle encoder data, heel and toe contact information via force sensing resistors in the shoe insoles were recorded wirelessly. The recorded data were processed to determine heel strikes and confirm the gait events determined by the finite state machine. Testing with able-bodied subjects verified that the overall HNP system was functional for evaluation in individuals with SCI.

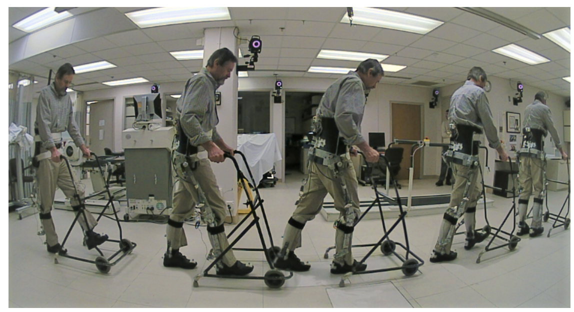


Fig. 9. Able body walking trial using HNP.

B. Walk with SCI

Three volunteers with motor complete SCI participated in testing the HNP during walking. All subjects volunteered and signed the local IRB-approved consent forms. Subject A used two percutaneous stimulation boards (Fig. 1b)), Subject B used one IST-16 and one surface stimulation board, and Subject C used one IRS-8 and one IST-16 stimulation board. Stimulation patterns for the gait cycle were programmed in the FNS control firmware in order to activate the various hip extensor, hip flexor, knee extensor, or knee flexor muscles through each subjects set of implanted electrodes. The stimulation patterns were integrated with the finite state machine to properly coordinate muscle activations with the exoskeletal brace constraints for restoring gait.

Once the participants donned the exoskeleton, testing was performed with the subjects walking within the work volume of a motion capture system (Vicon MX40, Vicon, Inc., Oxford, UK) to evaluate that the design specifications of the controller firmware have been met, as well as measure walking speed and cadence. Joint angles were measured using rotary encoders. The subjects initiated each step by pressing the go button on the wireless finger switch. Embedded controller data were sampled at 50Hz and the motion capture data were recorded at 200 Hz.

All participants were able to step with the HNP and the controller firmware for at least 22 left and right steps. Walking speed ranged from 0.03-0.06 m/s, step cadences ranged from 10-20 steps/min, change in hip joint angles ranged between $8.5° - 20.8°$, and change in knee joint angles ranged between $14.0° - 43.6°$ [11], [10]. Because the participants were able to step with the HNP controller firmware successfully with different stimulation board arrangements, the design specifications for the embedded controller are considered to have been satisfied. This demonstrated the potential to adapt the embedded controller technology for various individuals with SCI in robotic rehabilitation applications.

V. CONCLUSION AND FUTURE WORKS

The embedded control system design met its technical specification and satisfied the requirement criteria. The electronic hardware and firmware integrated with the hybrid orthosis, was able to acquired sensor data, executed muscle stimulation and the hydraulic actuator, transmitted data wirelessly, and powered the whole system by a battery with an extended runtime. The experimentation on able-bodied and SCI subjects proved that the HNP system is a fully functional exoskeleton for stepping after paraplegia, and has the potential for being a research platform for assistive robotics applications.

The limitation of current design lies in the conservative main controller selection and lacks of hardware reprogrammability. Future work will involve a hardware revision to improve the computational power, and real-time performance for more advanced gait assistance research, such as dynamic muscle stimulation modulation to reduce muscle fatigue, and use machine learning technique to enhance stability and motion coordination. The demonstrated modular hardware and firmware design strategy has progressively replaced or upgraded each individual system components or subsystem without influencing the entire system integrity.

The next exoskeleton architecture will include detachable sensor or actuator modules to allow maximized system modularity for different experimental configurations. In addition to having tighter real-time and computational requirements for sensing and motor control, the system has to be able to add and remove modules with minimum overhead. Therefore, a modular hardware configuration with multiple microcontrollers will be investigated, which will communicate over a shared digital communication bus. This distributed architecture allows offload computational tasks to subordinate processors, and to ensure real-time motion control requirements.

ACKNOWLEDGMENT

Special thanks friends and colleagues from CWRU, APT Center, Thanks subject volunteers who participated this study.

REFERENCES

[1] C. S. To, R. Kobetic, J. R. Schnellenberger, M. L. Audu, and R. J. Triolo, "Design of a variable constraint hip mechanism for a hybrid neuroprosthesis to restore gait after spinal cord injury," *IEEE/ASME Transactions on Mechatronics*, vol. 13, no. 2, pp. 197–205, 2008.

[2] R. Kobetic, C. S. C. To, J. J. R. Schnellenberger, M. L. M. Audu, T. C. T. Bulea, R. Gaudio, G. Pinault, S. Tashman, and R. R. J. Triolo, "Development of hybrid orthosis for standing, walking, and stair climbing after spinal cord injury.," *Journal of Rehabilitation Reseach and Development*, vol. 46, no. 3, pp. 447–462, 2009.

[3] L. E. Miller, A. K. Zimmermann, and W. G. Herbert, "Clinical effectiveness and safety of powered exoskeleton-assisted walking in patients with spinal cord injury: systematic review with meta-analysis.," *Medical devices (Auckland, N.Z.)*, vol. 9, pp. 455–66, 2016.

[4] A. B. Zoss, H. Kazerooni, and A. Chu, "Biomechanical Design of the Berkeley Lower Extremity Exoskeletong (BLEEX)," *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 2, pp. 128–138, 2006.

[5] A. Esquenazi, M. Talaty, A. Packel, and M. Saulino, "The ReWalk Powered Exoskeleton to Restore Ambulatory Function to Individuals with Thoracic-Level Motor-Complete Spinal Cord Injury," *American Journal of Physical Medicine & Rehabilitation*, vol. 91, no. 11, pp. 911–921, 2012.

[6] C. Y.S., S. M., and R. J., "Exploring the psychosocial impact of EKSO bionics technology," 2016.

[7] C. S. To, R. Kobetic, T. C. Bulea, M. L. Audu, J. R. Schnellenberger, G. Pinault, and R. J. Triolo, "Stance control knee mechanism for lower-limb support in hybrid neuroprosthesis," *Journal of Rehabilitation Research and Development*, vol. 48, no. 7, p. 839, 2011.

[8] M. Bortole, "Master Thesis Design and Control of a Robotic Exoskeleton for Gait Rehabilitation," *Thesis Master*, no. September, 2013.

[9] A. J. Del-Ama, Á. Gil-Agudo, J. L. Pons, and J. C. Moreno, "Hybrid FES-robot cooperative control of ambulatory gait rehabilitation exoskeleton," *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. March, p. 27, 2014.

[10] M. J. Nandor, S. R. Chang, R. Kobetic, R. J. Triolo, and R. Quinn, "A hydraulic hybrid neuroprosthesis for gait restoration in people with spinal cord injuries," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 9793, pp. 192–202, 2016.

[11] S. R. Chang, M. J. Nandor, L. Li, K. M. Foglyano, J. R. Schnellenberger, R. Kobetic, R. D. Quinn, and R. J. Triolo, "A Stimulation-Driven Exoskeleton for Walking after Paraplegia," vol. 44106, pp. 6369–6372, 2016.

[12] A. Software, "Arduino Software," 2010.

[13] C. King, "Fundamentals of wireless communications," in *2014 67th Annual Conference for Protective Relay Engineers, CPRE 2014*, pp. 470–474, 2014.

[14] H. Karl and A. Willig, *Protocols and Architectures for Wireless Sensor Networks*. 2006.

[15] J. A. Rios and E. White, "Fusion filter algorithm enhancements for a MEMS GPS/IMU," *National Technical Meeting of The Institute of Navigation (ION NTM)*, pp. 28–30, 2002.

[16] S. K. Kim, S. Hong, and D. Kim, "A walking motion imitation framework of a humanoid robot by human walking recognition from IMU motion data," in *9th IEEE-RAS International Conference on Humanoid Robots, HUMANOIDS09*, pp. 343–348, 2009.

[17] MathWorks Inc., "Build, run, and test real-time applications," 1994.

[18] K. A. Strausser and H. Kazerooni, "The development and testing of a human machine interface for a mobile medical exoskeleton," *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4911–4916, 2011.

[19] J. W. Stephen Trier, Tina Vrabec, "Using Functional Electrical Stimulation to Restore Movement to Individuals with Neuromuscular Disabilities - MATLAB & Simulink," 2018.